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ON THE PERFORMANCE OF THE EXPERIMENTAL
BAINITIC CHROMIUM - MOLYBDENUM RAIL STEEL
TP 3726E

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ON THE PERFORMANCE OF THE EXPERIMENTAL BAINITIC CHROMIUM - MOLYBDENUM RAIL STEEL TP 3726E

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Canadian Pacific Limited
Report No. S739-82
April, 1982

Prepared for
Transport Canada
Transportation Development Centre

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REPORT DOCUMENTATION FORM

1. Transport Canada Report No.	2. TDC Project No	3. Recipient's Catalogue No
TP 3726E	5122	

4. Title and Subtitle	5. Report Date
On The Performance Of The Experimental Bainitic Chromium - Molybdenum Rail Steel	APRIL 1982
	6. Performing Organization Report No

7. Author(s)	8. Transport Canada File No
H. Ghonem	D1465-147

9. Performing Organization Name and Address	10. DSS File No
Canadian Pacific Limited Department of Research Windsor Station Montreal, Quebec H3C 3E4	11ST.T8200-5-5520/1
	11. DSS or Transport Canada Contract No OST77-00100

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Transportation Development Centre (TDC) 1000 Sherbrooke Street West P.O. Box 549, Place de l'aviation Montreal, Quebec H3A 2R3	Final
	14. Sponsoring Agency Code TDC 5122

15. Supplementary Notes	16. TDC Project Officer
	W.S.C. McLaren

17. Abstract

This report summarizes a development and test program to appraise the performance of experimental chromium-molybdenum (bainitic) alloy steel rails.

The report reviews the background of the program, the results of wear assessments conducted at the Facility for Accelerated Service Testing (F.A.S.T.) in Pueblo, Colorado, and research results relating to welding of the test rails.

Findings of the test program have shown that the experimental bainitic chromium-molybdenum rail cannot be viewed as a premium rail.

18. Key Words	19. Distribution Statement
Railroads, rails, steel, chromium-molybdenum, bainitic, alloys, metals, metallurgy	

20. Security Classification (of this report)	21. Security Classification (of this page)	22. No. of Pages	23. Price

TDC CDT 79-005

FORMULE DE DOCUMENTATION POUR RAPPORT

1	N° du rapport Transports Canada	2	N° de l'étude — CDT	3	N° de catalogue du destinataire
	TP 3726E		5122		

4	Titre et sous-titre	5	Date du rapport
	On The Performance Of The Experimental Bainitic Chromium - Molybdenum Rail Steel		avril 1982
		6	N° du rapport de l'organisme exécutant

7	Auteur(s)	8	N° de dossier Transports Canada
	H. Ghonem		D1465-147

9	Nom et adresse de l'organisme exécutant	10	N° de dossier — ASC
	Canadien Pacifique Limitée Département de recherche Gare Windsor Montréal, Québec H3C 3E4		11St.T8200-5-5520/1
		11	N° de contrat — ASC ou Transports Canada
			OST77-00100

12	Nom et adresse de l'organisme parrain	13	Genre de rapport et période visée
	Centre de développement des transports (CDT) 1000 ouest, rue Sherbrooke C.P. 549, Place de l'aviation Montréal, Québec H3A 2R3		Final
		14	Code de l'organisme parrain
			CDT 5122

15	Remarques additionnelles	16	Agent de projet — CDT
			W.S.C. McLaren

17 Resume

Ce rapport résume les travaux d'évaluation de la performance d'un rail expérimental en acier (bainitique) au chrome-molybdène menés dans le cadre d'un programme d'essais et de développement consacré à ce type de rails.

Il relate l'historique du programme et donne les résultats des tests d'usure réalisés aux installations "Facility for Accelerated Service Testing (F.A.S.T)" à Pueblo, Colorado, ainsi que ceux de la recherche intéressant le soudage des rails en question.

Le programme d'essais débouche sur la conclusion que le rail expérimental en acier au chrome-molybdène ne se qualifie pas comme un rail de première catégorie.

18	Mots-clés	19	Diffusion
	Voies ferrées, rails, acier, chrome-molybdène, bainite, alliages, métaux, métallurgie		

20	Classification de sécurité (de ce rapport)	21	Classification de sécurité (de cette page)	22	Nombre de pages	23	Prix

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I. Introduction

In 1973, the Research Department of Canadian Pacific initiated a study of rail metallurgy as part of its cost sharing track/train dynamics program with Transport Canada. The major objective of this study was to investigate routes that could lead to improvement in the operational life of rail steel in the Canadian traffic environment and conditions. To achieve this objective, many aspects related to the rail steel structure were explored in a preliminary work by Kalousek and Beynon (1). In this work it was concluded that rail life, all variables being constant, could be increased by refining both grain size and spacings between pearlite lamella - a conclusion that has been shared by several other authors (2-5). Several methods are known to achieve this type of refinement, such as heat treating the existing rail; alloying the rail steel with elements that control the grain size and lamella spacings; or, finally, by combining the heat treatment route with the alloying method. The different facets of each method were discussed in Ref (1) and for economic reasons the alloying method was selected as a practical route for Canadian Pacific to follow in its attempts to improve the rail steel structure. Commercially available alloyed rails, or those being experimentally investigated in the U.S., Europe, Japan and Australia at that time, 1975, were analyzed and compared (1). Out of these compositions, shown in Table 1, the chromium-molybdenum rail proposed by Climax Molybdenum Co. of Michigan appeared to be the most desirable for future premium alloyed rails.

Having selected the rail type, and in order to optimize the rail microstructure in gradual manner, it was suggested that three phases be followed in the refining of this microstructure: the first, to obtain a rail with a subsurface structure having a hardness level of 340-360 BHN:

the second phase, to reach 360-380 BHN, while the last would aim for 380-450 BHN. To carry out the first phase, an ingot casting heat of Cr-Mo steel rolled into 132 lb/yd was produced by Algoma for Canadian Pacific in October 1975.

Realizing the difficulties associated with a new production, major problems were encountered due to an abnormal straightening pattern of the Cr-Mo rails during cooling on the hot bed. Some of the rails developed excessive curvature in the vertical or the lateral planes resulting in excessive camber or sweep limits. It was subsequently difficult to test this rail under field conditions due to the limited number of valid straight lengths from this heat. A series of laboratory tests was, however, carried out on this heat and its analysis was detailed in Ref. (6). A result of this analysis was that streaks of martensite and upper bainite, with different densities, were observed to be located at segregated regions in the center of the web of this rail. This form of streaks, shown in Figure 1a, could considerably reduce a fatigue crack initiation period in the segregated regions and thus effect the service life of the rail length.

In an effort to reduce such segregation and thus eliminate web streaks a second heat (9273B) of continuously cast Cr-Mo rail was made in early 1977. It was intended that this heat also fall into the phase I category; i.e. achieving a rail structure with a hardness level of 340-360 BHN. Metallurgical examinations of this heat showed, however, that the average head hardness of this heat was over 380 BHN. Furthermore, its microstructure was found to be dominantly bainitic*. Canadian Pacific, as well

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*Bainite is a structure formed by relatively rapid cooling of austentite, consisting of needles of cementite and highly strained ferrite.

as many other railraods in the world, did not have previous experience with the use of bainitic steel in railways; therefore, the risk associated with testing such steel in the heavy haul line of the Pacific region, where a need for high hardness rail exists, could not be calculated. It was consequently decided that, in addition to laboratory testing, a field test using the track loop of the facilities for Accelerated Service Testing (F.A.S.T.) in Pueblo, Colorado, should be carried out to estimate the wear and fatigue performance of the bainitic heat. A series of reports detailing the laboratory testing was published in 1979 and 1980, see Refs. (6 & 7). This report is a summarized description of the field test and its results.

II. Field Tests on F.A.S.T.

II.1. Test Arrangements

In February 1978, 55 lengths of Cr-Mo(B)* arrived at the transportation test center in Pueblo for the purpose of accelerated metallurgical service testing. To obtain preliminary data on the general performance of this bainitic rail two rails were placed on a tangent track of section 11 of the F.A.S.T. loop. During a period of 15 months the two rails accumulated 140 million growth tons (MGT) and were then removed in May 1979 due to bolt hole cracks in both and the occurrence of a transverse defect over one bolt hole in one of the rails. It was at that time suggested that the practice of rail-end-build-up, which was used with this rail alloy, was the reason for the rail end failures.

At the end of this test, the average head profile of the two rails was obtained and compared to the new rail. No evidence of surface wear

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*Cr-Mo(B) will be used in the report to identify the Chromium-Molybdenum rail produced by Algoma as heat 9273B having a bainitic microstructure.

was observed . This type of test, while not valid for estimating the performance of Cr-Mo(B) on curves, was regarded, however, as a basis for further testing of the rail on curved sections of the F.A.S.T. loop.

To install the remaining Cr-Mo(B) rails in the loop track, 53 rail lengths were welded at Burlington Northern welding plant in Pueblo. The welding cycle used in this operation is shown in Table 2 and compared to that established by Canadian Pacific by using the welding facilities of the Transcona welding plant. As a result of the welding process in Burlington Northern, high hardness measurements were found to exist at the top of the rail end surface. To avoid brittle steel characteristics at the weld regions, rail ends were tempered to modify this hardness level. Twenty of these rails, welded and tempered, were included in the third experimental metallurgy test which was underway in sections 3 and 17 of the F.A.S.T. loop.

The Cr-Mo(B) rails were placed in section 3 which has a 5° curvature, a 2% grade and a $\frac{1}{40}$ cant. Seven other different rail types, in addition to Cr-Mo(B), were to be tested in this section; all of these were 132 lb/yd. One of these rails was a chromium-molybdenum rail manufactured by CF&I and known as a weldable grade which requires no post heat cycles during welding; its chemistry is shown in Table 3 and is compared with Cr-Mo(B). Compositions of other rails tested in this experiment are also shown in the same Table. In section 3, the experimental test was designed so that rails of a given metallurgy were welded together while segments of different metallurgies were linked by mechanical joints. The layout of all test metallurgies in section 3 followed a tie number sequence as listed in Table 4.

In this experiment, which is detailed in an excellent paper by

R. Steele and R. Reiff (8), rails were subjected to programmed regimes of lubricated and dry conditions so that wear and metal flow in both regimes could be studied and compared. By early June 1980, the rails in section 3, including the 20 length of Cr-Mo(B), had accumulated 47 MGT during two cycles; one cycle (33 MGT) was carried out with unlubricated rails. At that time corrugations with random wave lengths were observed on the surface of some of some of the Cr-Mo(B) while others of the same rail had developed welded rail-end batter. To control this form of surface disturbance, rails were ground twice on a selective basis. In June 1981 the twenty lengths of Cr-Mo(B) were removed from the F.A.S.T. loop after an accumulation of 115 MGT, consisting of lubricated and dry cycles.

III. Wear Performance

The main parameter that was studied during the field tests of Cr-Mo(B) and other rails in F.A.S.T. was high rail curve wear (8). Wear measurement included gage face wear, head height and total head area loss. These measurements which were obtained using a "snap gage" of accuracy ±0.002 are illustrated in Fig. 1. For the Cr-Mo(B) these measurements were taken at intervals of approximately 2 months. Such measurements were compared each time with corresponding measurements taken on other rail metallurgies. These profile comparisons are shown in Figures 2 and 3. Furthermore, direct snap gage measurements vs. tonnage accumulations are shown in Figure 5 for Cr-Mo(B). From the aforementioned figures an average wear rate was calculated, and results are shown in Tables 5 and 6.

Hardness measurements of the running surface and gauge face of all tested rail for lubricated and dry regimes were obtained (8) and are shown in Table 7. Table 8 shows these hardness values as compared to those of

Cr-Mo(B). Furthermore, Figure 4 shows the gauge face wear rate in relation to the running surface hardness for rails tested in section 3.

From the analysis of wear data and hardness measurements of Cr-Mo(B), as summarized before, it could be concluded that Cr-Mo(B) rail performance in the dry regime was similar to most of the premium rails. However, in the lubricated regime, although its surface and gauge hardness were higher than all of the test rails with the exception of SiCr, its wear performance was virtually the same as the standard rail. Furthermore, when the wear rate was related to the gauge face hardness in both lubricated and dry conditions, the performance of Cr-Mo rail was the lowest among all premium rails.

IV. Welding Performance

As mentioned in the previous section, Cr-Mo(B) rails were welded at the Burlington Northern welding plant using what is described in Ref. (8) as a short delay practice and long delay practice. The difference in the two practices was the time delay introduced in the post heat cycles. The apparent difference between the two practices in the Heat Affected Zone (HAZ) of the Cr-Mo(B) rail was that the short delay practice can cause the distance between the HAZ boundaries at the running surface to be about twice as large as that produced by the long delay practice. Figure 5 shows the HAZ for a weld produced using the short delay practice. Surface hardness is obtained from the two practices as a function of distance from the weld bond line, shown in Figures 6 and 7.

When samples of this weld were metallurgically analyzed, their matrix structure was typical of that shown in Figures 6, 7 and 8 about which the following was concluded.

i) The microstructure of the head, mid-web and base included martinsite bands with a percentage of 20-40%.

ii) Knops hardness number of over 700 was measured on the martinsite bands which indicated the untempered martinsite.

In order to reduce the amount of martinsite and improve the high hardness values on the running surface of the weld, all Cr-Mo(B) welds were tempered, as mentioned before, by heating the rails to 1000°F for 20 minutes. In spite of this, some of the Cr-Mo(B) rails exhibited severe rail-end batter. A typical surface profile of the batter depth is shown in Figure 9. At 90 MGT the batter depth reached 0.09" and was expected to reach 0.15" by 150 MGT. To eliminate the effect of the surface batter, the Cr-Mo(B) was ground twice on a selective basis. Figure 10 shows the change in weld batter depth of Cr-Mo(B) from the first remedial grinding as compared to that of Cr.V rail in section 17 which was also ground twice. This indicates that no improvement had occurred in the rail end surface of Cr-Mo(B) after grinding, and the batter depth continued to increase as the amount of accumulated tonnage increased.

V. Conclusions

Data presented in this report, as detailed in Reference (8), concerning the performance of the bainitic chromium-molybdenum rail steel, with the specific composition shown in Table 1(b), indicates the following:

1. Under dry test conditions, wear characteristics of Cr-Mo(B) did not show any significant improvement when compared with different premium rails, a list of which is shown in Table 1(a)
2. Under lubricated conditions, wear characteristics of Cr-Mo(B) were comparable only to the standard carbon rail steel

3. Cr-Mo(B) requires a special flash butt welding cycle which involves long periods of preheat and postheat cycles. This makes the welding cycle longer and more expensive than any premium rail type. Furthermore, no success was achieved in obtaining a welding cycle for this rail that could be valid for service conditions.

The obvious conclusion is that the bainitic chromium-molybdenum steel (heat 9273B) cannot be viewed as a premium rail steel.

Last comment: Heat 9273B was intended to be a pearlitic rail steel with hardness values falling in the range of 340-360 BHN. It emerged, however, as a baintic rail with hardness values exceeding 400 BHN. This outcome indicates a less than adequate control of chemical composition and hardenability during the steel making process.

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MANUFACTURER	RAIL TYPE		U.T.S. ksi	U.T.S. MPa	0.2% Y.S. ksi	0.2% Y.S. MPa	El %	R.A. %	HARDNESS BHN
	STANDARD AREA		134	924	74	510	11	30	255
BETHLEHEM STEEL	HEAT TREATED	FULLY HEAT TREATED	177	1,220	126	870	13	30	365
U.S. STEEL	HEAT TREATED	HEAD HARDENED	183	1,260	132	910	12	33	380
NIPPON STEEL	HEAT TREATED	HEAD HARDENED	165	1,140	120	830	17	50	360
NIPPON KOKAN	HEAT TREATED	HEAD HARDENED	165	1,140	120	830	17	50	360
RUSSIAN	HEAT TREATED	FULLY HEAT TREATED	181	1,250	119	820	14	40	380
CF&I	ALLOYED	Hi Si	142	980	75	520	11	14	285
BRITISH STEEL	ALLOYED	Cr	164	1,130	100	690	11	17	325
ALGOMA	ALLOYED	Cr	150	1,035	95	655	9	17	320
CF&I	ALLOYED	Cr-Mo	181	1,250	124	855	12	20	365
KLOCKNER	ALLOYED	Cr-Mo-V	166	1,145	102	703	12	20	325
SYDNEY	ALLOYED	Mn-Cr-V	150	1,035	102	703	12	18	325
SYDNEY	ALLOYED	Cr-Si-Nb	165	1,140	102	703	10	16	340
KRUPP	ALLOYED	Cr-Si	165	1,140	98	676	12	20	315
THYSSEN	ALLOYED	Cr-Si-V	164	1,130	99	683	12	20	320

Table: 1(a) Typical Tensile Properties and Hardness of Several Types of Rail

MANUFACTURER	RAIL TYPE		C	Mn	Si	Cr	Mo	V	Nb
	STANDARD AREA		.80	.90	.20	-	-	-	-
BETHLEHEM STEEL	HEAT TREATED	FULLY HEAT TREATED	.80	.90	.20	-	-	-	-
U.S. STEEL		HEAD HARDENED	.80	.90	.20	-	-	-	-
NIPPON STEEL		HEAD HARDENED	.65	.90	.20	-	-	-	-
NIPPON KOKAN		HEAD HARDENED	.65	.90	.20	-	-	-	-
RUSSIAN		FULLY HEAT TREATED	.75	.90	.30	-	-	-	-
CF&I	ALLOYED	Hi Si	.75	.80	.65	-	-	-	-
BRITISH STEEL		Cr	.75	1.25	.35	1.15	-	-	-
ALGOMA		Cr	.75	.65	.25	1.15	-	-	-
CF&I		Cr-Mo	.75	.90	.25	.8	.18	-	-
KLOCKNER		Cr-Mo-V	.65	.80	.30	1.00	.10	.10	-
SYDNEY		Mn-Cr-V	.70	1.65	.20	.30	-	.10	-
SYDNEY		Cr-Si-Nb	.70	1.10	.55	.80	-	-	.06
KRUPP		Cr-Si	.70	1.05	.75	1.00	-	-	-
AUG. THYSSEN		Cr-Si-V	.65	1.05	.60	1.15	-	.20	-

Table:1(b) Typical Chemical Composition of Several Types of Rails

A. Welding Cycle Performed at Burlington Northern Plant (December 1989 and February 1979)

Flash off
7 preheat cycles (7.5 seconds on, 2.5 seconds off)
Forging
10 postheat cycles (3 seconds on, 10 seconds off)
Shear

B. Welding Cycle Performed at Canadian Pacific's Transcona Welding Plant (March 1978)

Flash off
7 preheat cycles (2.5 seconds on, 1 second off)
Forging
10 postheat cycles (3 seconds on, 2 seconds off)
Shear

Table 2: Welding Cycles of Cr-Mo(B)

Rail Type \ Weight Percent	C	Mn	P	S	Si	Cr	Mo	V
Std	0.76	0.86	0.022	0.024	0.18	-	-	-
FHT	0.81	0.93	0.018	0.041	0.20	-	-	-
HH	0.77	0.83	0.021	0.030	0.17	-	-	-
NHH	0.76	0.93	0.020	0.020	0.22	-	-	-
SiCr(HH)	0.76	0.82	0.020	0.006	0.82	0.50	-	-
SiMn(HH)	0.76	1.24	0.023	0.009	0.84	-	-	-
Different Manufacturer 1% Cr	0.71	0.73	0.014	0.021	0.27	1.16	-	-
Different Manufacturer 1% Cr	0.73	1.30	0.023	0.026	0.30	1.25	-	-
Different Manufacturer 1% Cr	0.75	0.88	0.030	0.027	0.23	0.95	-	-
Different Manufacturer Cr V	0.67	1.15	0.009	0.013	0.34	1.11	-	0.110
Different Manufacturer Cr V	0.72	1.72	0.014	0.030	0.22	1.04	-	0.087
Cr-Mo(CF&I)	0.72	0.79	0.009	0.023	0.25	0.78	0.21	-
Cr-Mo(B)	0.79	0.60	0.026	0.016	0.26	0.61	0.17	-

Table 3: Composition of Rails Tested in F.A.S.T. 3rd Metallurgical Experiment

Rail Type \ Tie Position	Outer Rail	Inner Rail
Std	→ 210	→ 220
HH	210-330	221-342
Cr-Mo(B)	330-450	342-464
Cr-Si	450-570	464-582
1% Cr(British)	572-724	582-734
Cr-Mo(CF&I)	724-843	734-855
HH	843-964	855-976
Std	964-1084	976-1096
FHT	1084-1205	1096-1216
HH	1205-1325	1216-1337
Std	1325-1446	1337-1457
Cr-Mo	1447-1567	1457-1577
Cr-Si	1567-1696	1578-1701
1% Cr(CF&I)	1696-1810	1701-1822
Cr-Mo(CF&I)	1810-1922	1822-1943
Std	1929-2049	1943-2063
HH	2064-2199	2063 →

Table 4: Rail Tested in Section 3 of F.A.S.T. by Tie Number

SECTION 3	INCHES PER MGT LUBRICATED	AVG	UNLUBRICATED	AVG
Standard				
Tie #110 to 200	0.0010		0.0059	
Tie #977 to 1429	0.0009	0.0010	0.0065	0.0066
Tie #1348 to 1429	0.0011		0.0069	
Tie #1955 to 2040	0.0011		0.0069	
Head Hardened (Std)				
Tie #220 to 314	0.0006		0.0020	
Tie #865 to 954	0.0008	0.00075	0.0024	0.0023
Tie #1217 to 1314	0.0007		0.0027	
Tie #2086 to 2177	0.0009		0.0021	
SiCr (HH)				
Tie #475 to 554	0.0007		0.00160	
Tie #1591 to 1669	0.0006	0.00065	0.00185	0.0017
1% Cr				
Tie #600 to 707	0.0006		0.0027	
Tie #1716 to 1801	0.0007	0.00065	0.0031	0.0029
CrMo (CF&I)				
Tie #751 to 830	0.0006		0.0028	
Tie #1841 to 1919	0.0007	0.00065	0.0031	0.0029
CrMo(B)				
Tie #354 to 428	0.0009		0.0039	
Tie #1470 to 1544	0.0009	0.0009	0.0036	0.0036
FHT				
Tie #1096 to 1190	0.0007		0.0031	

Table 5: Gauge Face Wear Rates of Rails in Section 3 of F.A.S.T. (8)

	Dry	Lubricated
Cr-Mo(B)	1.00	1.00
Std	1.1	1.83
HH	0.83	0.63
SiCr(HH)	0.72	0.47
1% Cr(BSC)	0.72	0.81
Cr-Mo(CF&I)	0.72	0.81
FHT	0.78	0.86

Table 6: Ratio of Rail Wear Rate to that of Cr-Mo(B) for All Tested Rails on Section 3 of F.A.S.T.

Metallurgy	Running Surface	Gage Face
Standard	324	314
Fully Heat Treated	366	386
Head Hardened (HH)	355	381
Silicon Chrome (SiCr(HH))	391	405
Cr-Mo(CF&I)	344	353
Cr-Mo(B)	383	398
Chrome Vanadium	372	365
1% Chrome (BSC)	348	353

Table 7: Hardness Measurements (BHN) on the Surface and the Gauge Face of Tested Rails

Metallurgy	Running Surface Ratio	Gage Face Ratio
Cr-Mo(B)	1.00	1.00
Standard	0.85	0.79
Fully Heat Treated	0.95	0.97
Head Hardened	0.93	0.96
Silicon Chrome	1.02	1.02
Cr-Mo(CF&I)	0.90	0.89
Chrome Vanadium	0.97	0.92
1% Cr	0.91	0.89

Table 8: Ratio of Hardness Measurements of Tested Rails to that of Cr-Mo(B)

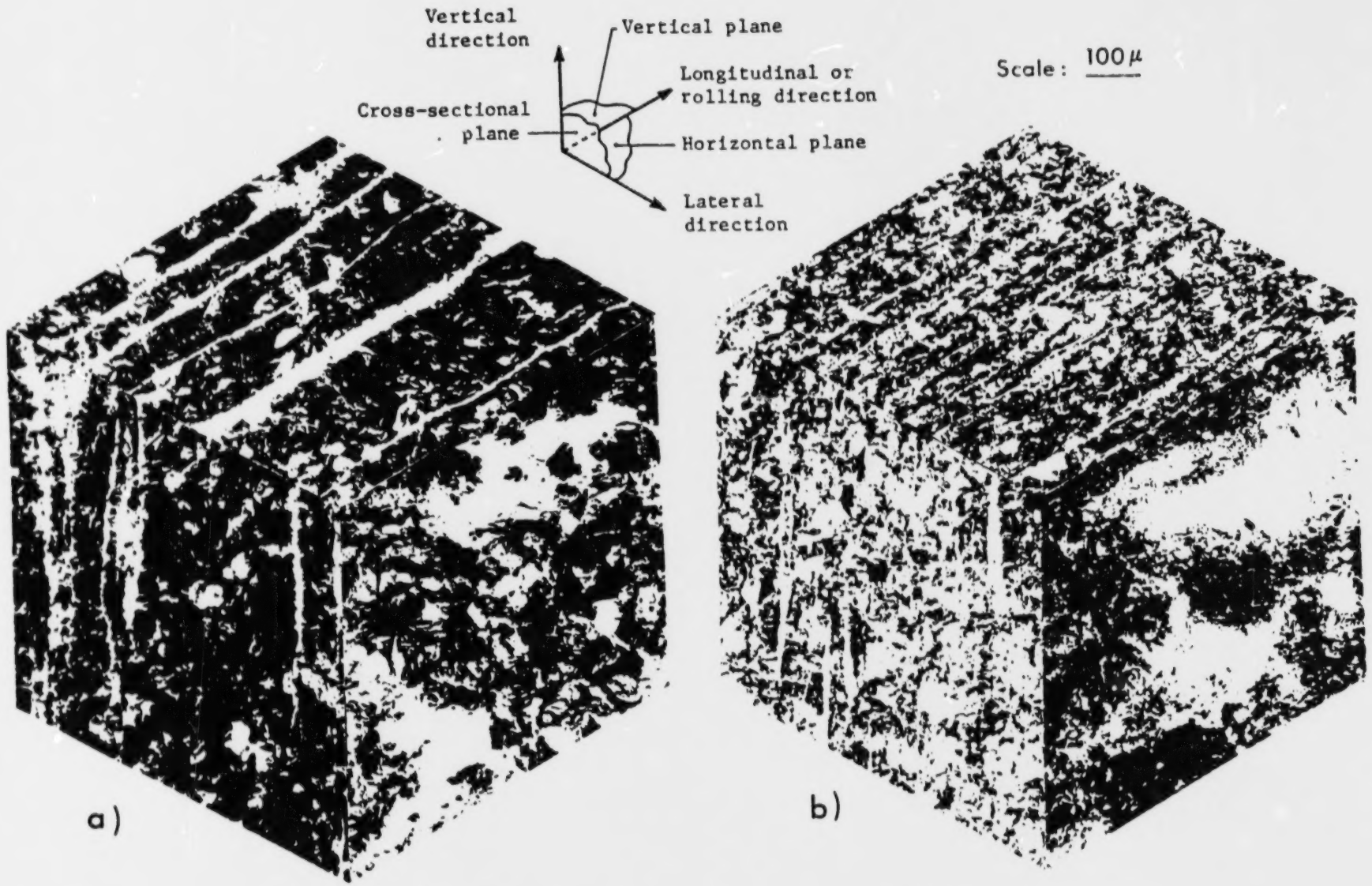


Figure 1a: Microstructure of Cr-Mo Web Material, on the Three Processing Planes Depicting the Shape of 'Streaks' a) Cr-Mo I (C5599) b) Cr-Mo II (9237B)

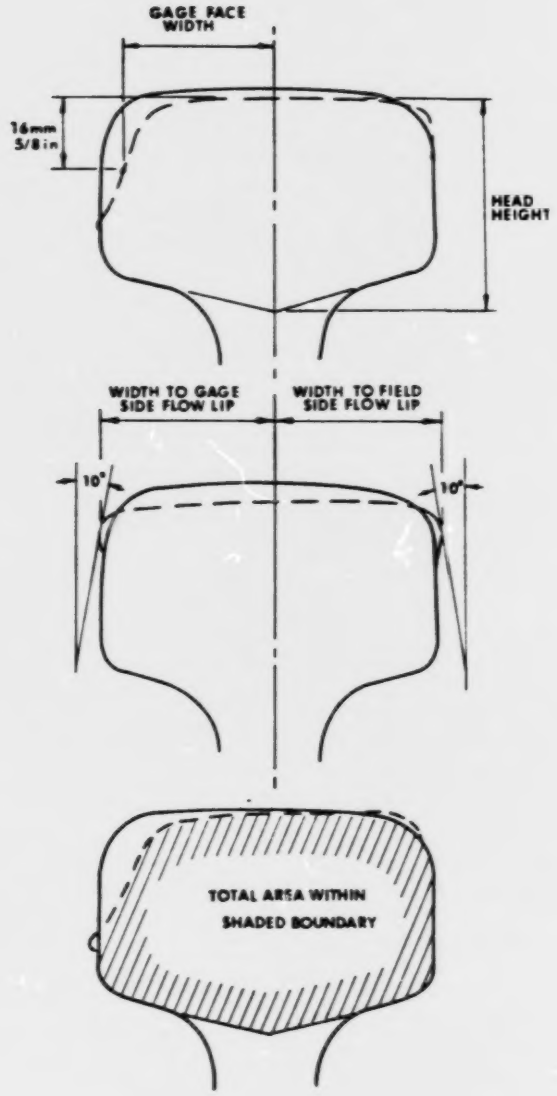
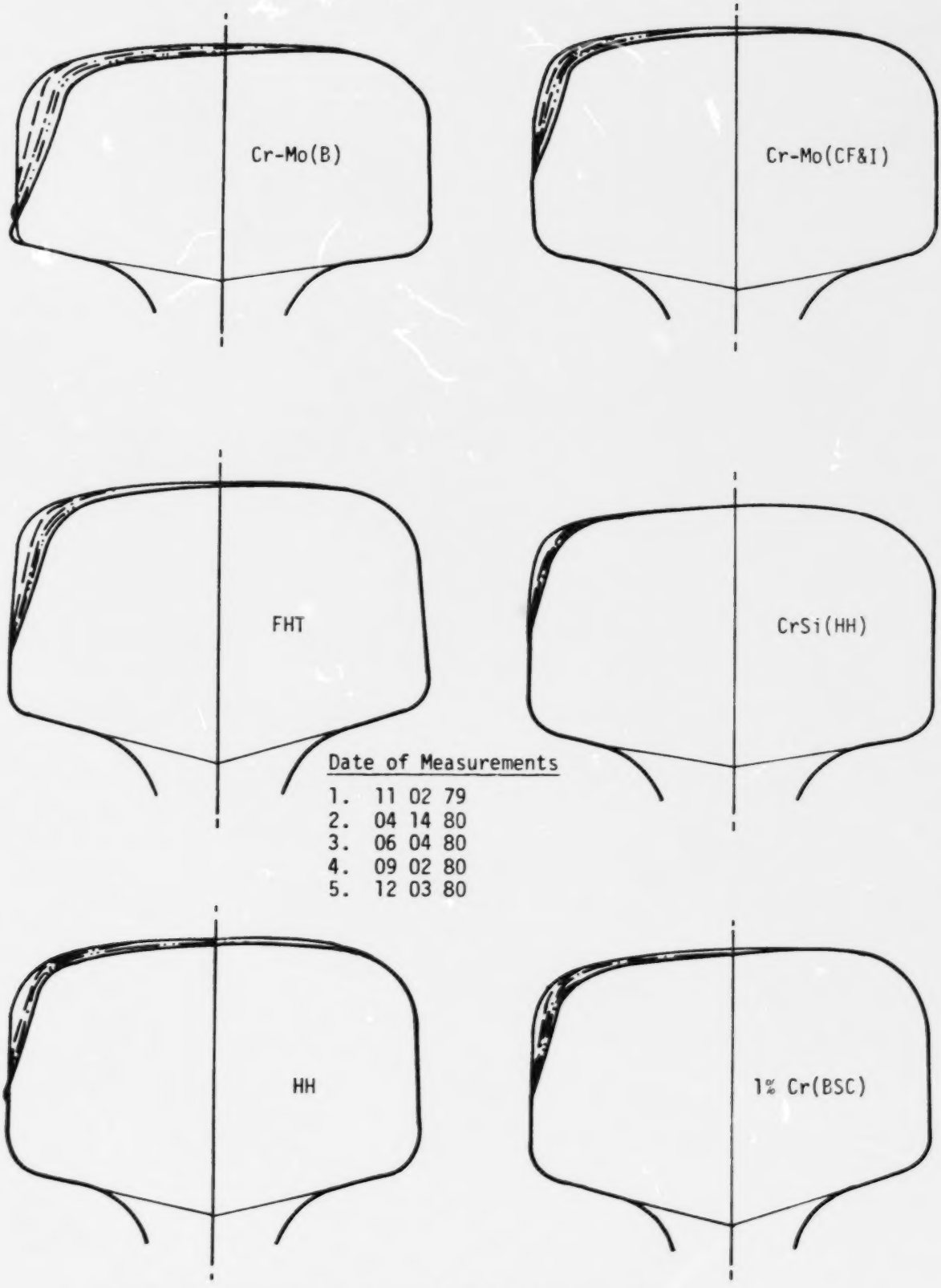


Figure 1: "Snap Gage" Measurements on the Rail Head (8)



Date of Measurements

1. 11 02 79
2. 04 14 80
3. 06 04 80
4. 09 02 80
5. 12 03 80

Figure 2: Comparison of Tested Rails Head Profile

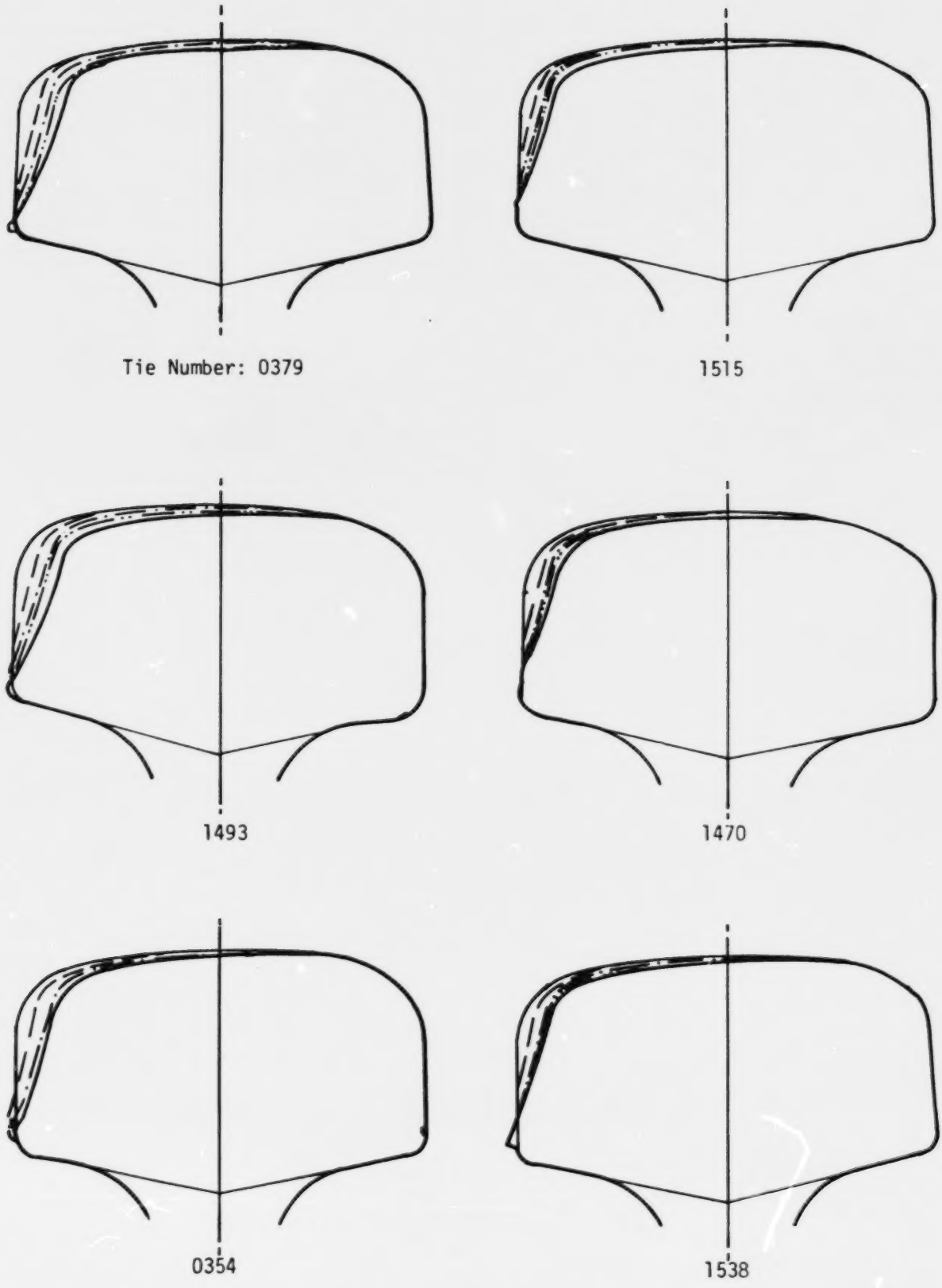


Figure 3: Comparison of Cr-Mo(B) Rail Head Profile at Different Tie Positions on Section 3 of F.A.S.T.

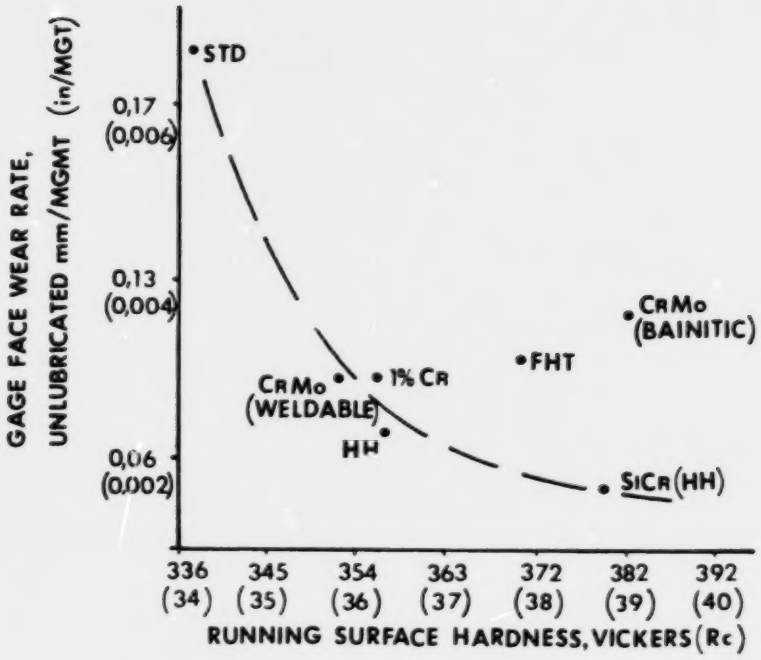


Figure 4: Gauge Face Wear Rate in Relation to the Running Surface Hardness

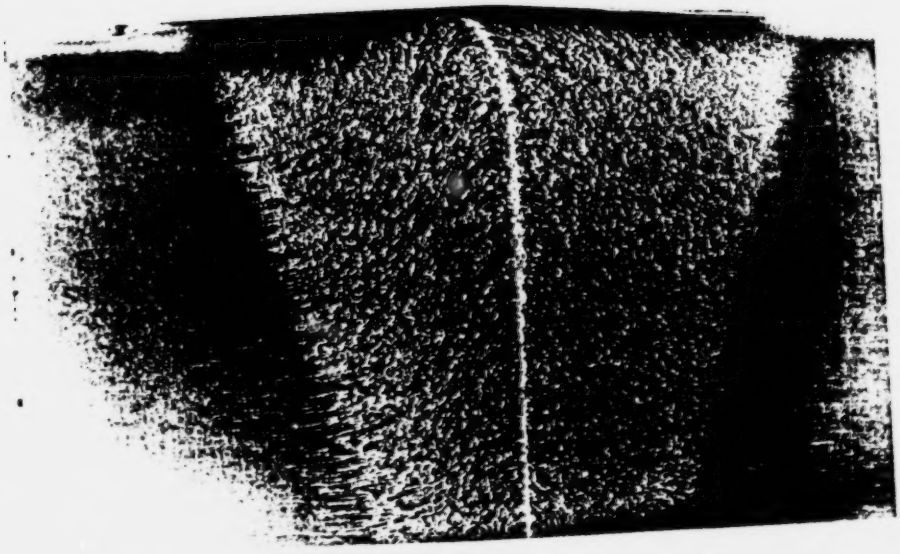


Fig. 5(a) Heat Affected Zone for Short Delay Welding Practice.

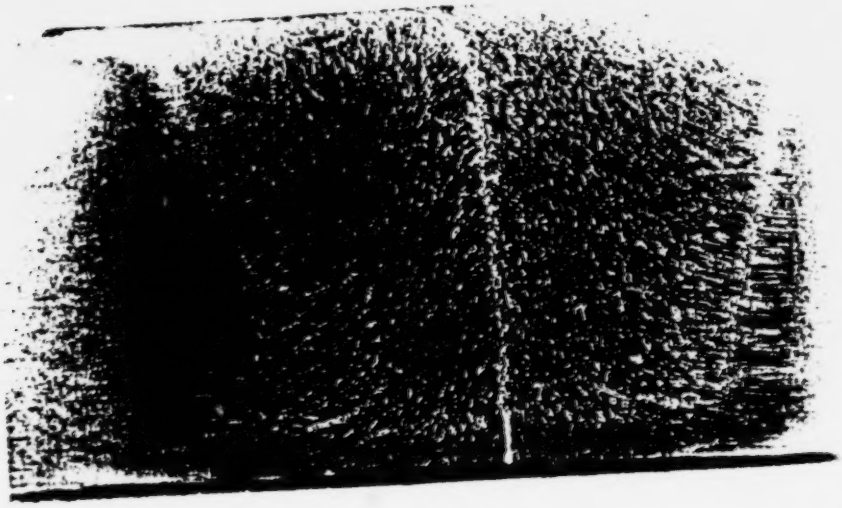


Fig. 5(b) Heat Affected Zone for Long Delay Welding Practice

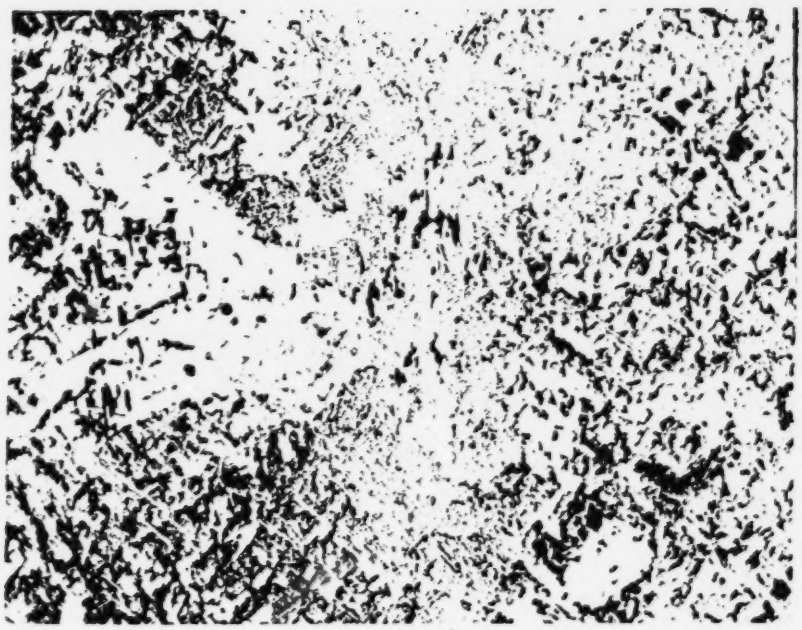


Figure 6: Microstructure of a Welded Base Section

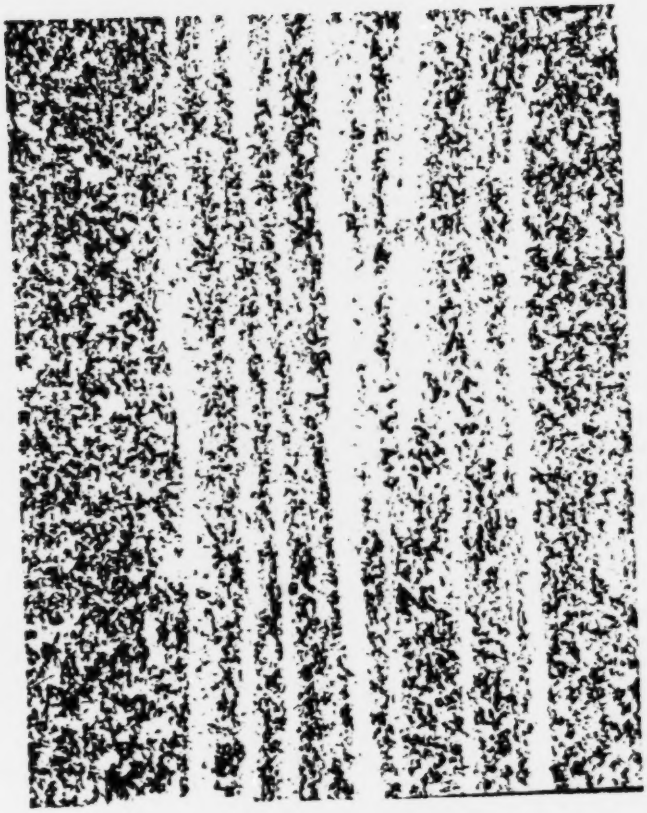


Figure 7: Microstructure of a Welded Head Section

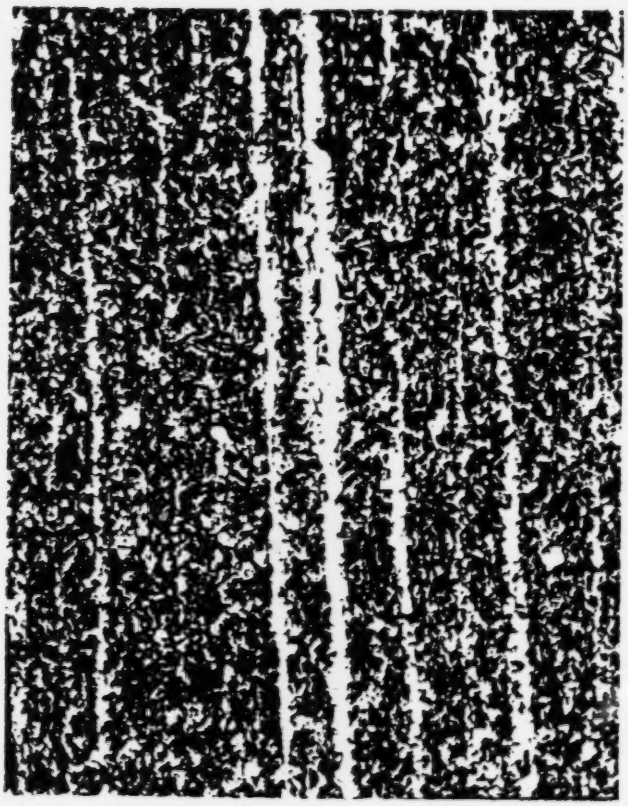


Figure 8: Microstructure of a
Welded Base Section

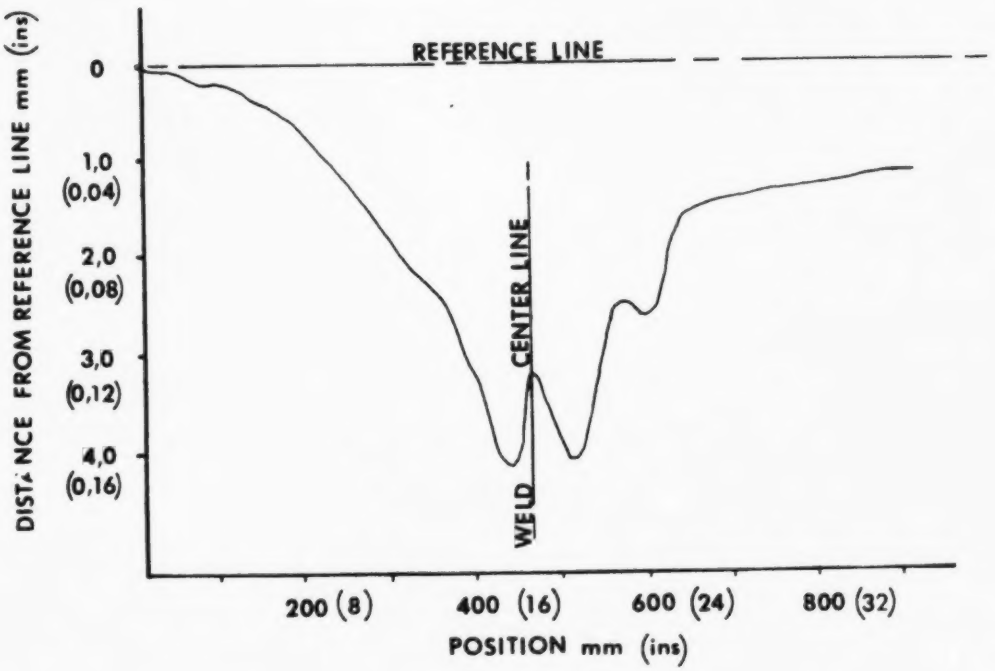


Figure 9: A Typical Surface Profile of the Batter Depth for Cr-Mo(B)

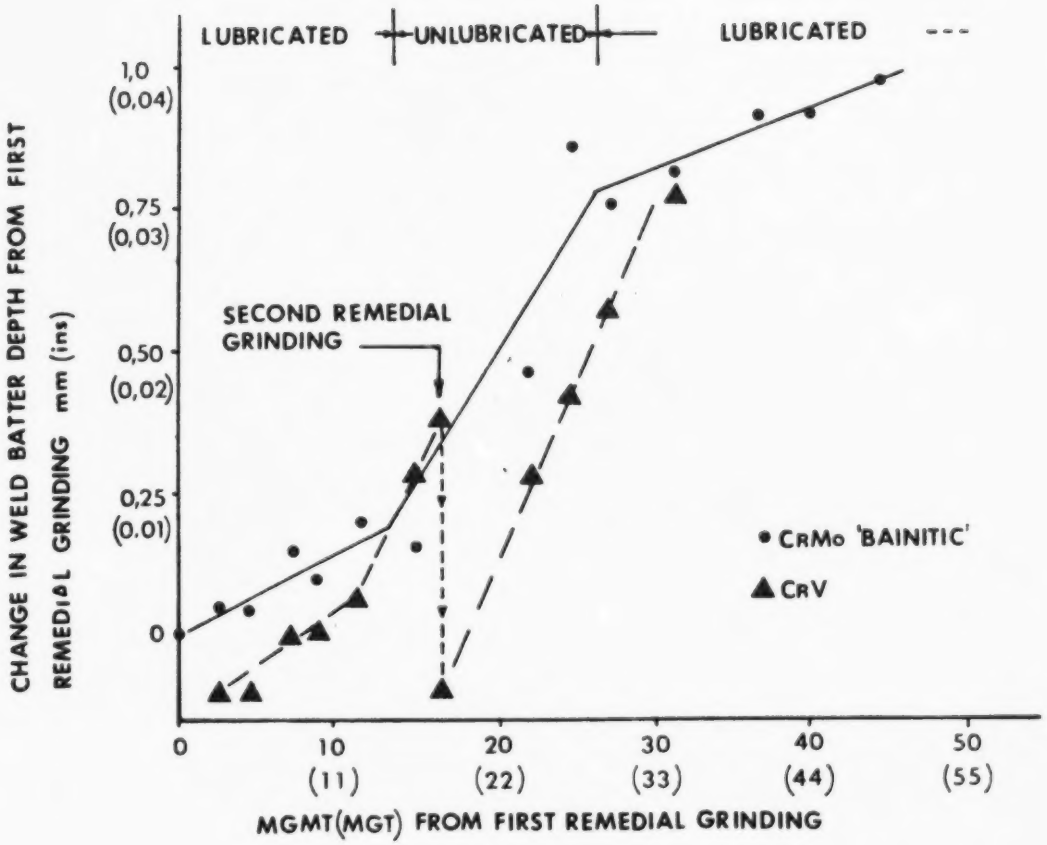


Figure 10: Changes in Weld Batter Depth of Cr-Mo(B) From the First Remedial Grinding as Compared to that of Cr-V Rail in Section 17 of F.A.S.T.